Developing a Predictive Capability for Bioluminescence Signatures

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LONG-TERM GOALS

Bioluminescence represents an operational threat to naval nighttime operations because the flow field associated with their motion stimulates naturally occurring plankton. In the littoral, the primary sources of bioluminescence are dinoflagellates, common unicellular plankton that are also known to form red tides. Dinoflagellate bioluminescence is stimulated by flow stress of sufficient magnitude to cause cell deformation, such as in the boundary layers of swimming animals, in separated flow of the wakes of animals, fixed objects, and ships, and in breaking surface waves, leading to spectacular displays of bioluminescence during periods of high dinoflagellate abundance. The oceans can be considered a luminescent “minefield” where bioluminescence is stimulated by flow disturbance. The bioluminescent “signatures” of some swimming fish are distinct enough to differentiate species; nocturnally foraging predators may use bioluminescent wakes to locate their prey.

The bioluminescence signature of a moving object depends on the bioluminescence potential of the organisms (related to their species abundance), the volume of the flow regions associated of sufficient shear stress, and its detectability from a surface observer based on radiative transfer of the light through the water and surface interface, as well as surface ambient light conditions. We are interested in predicting bioluminescence signatures, specifically in developing the capability to model flow stimulated bioluminescence and applying the model to a computational fluid dynamics model of the flow field of a moving object, and exploring mitigation strategies that reduce the bioluminescence signature to reduce the threat of detection of moving underwater vehicles.

OBJECTIVES

An extremely challenging goal is the need to predict the intensity and spatial “footprint” of bioluminescence signatures of naval relevance. Advances in computational fluid dynamics (CFD) led by PI Hyman make it possible to model the flow around a moving object, and now a new bioluminescence stimulation (BIOSTIM) model developed by PI’s Deane and Stokes (Deane and

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Stokes 2005) provides an initial capability to estimate bioluminescence levels as a function of flow properties, specifically fluid shear stress, which we have previously shown to be the flow property most closely correlated with flow-stimulated bioluminescence in primarily laminar flows (Latz et al. 1994; Latz et al. 2004; Latz and Rohr 1999; Maldonado and Latz 2007).

The overall scientific objectives of this project are to: (1) perform "calibration" experiments to determine the relationship between bioluminescence stimulation and fluid shear stress; (2) update the BIOSTIM model based on the calibration experiments results to include a high shear stress stimulation component; (3) evaluate computational approaches using Reynolds-averaged Navier-Stokes (RaNS) and Direct Numerical Simulation (DNS) solvers, to determine which is more suitable for bioluminescence predictions; (4) validate the updated BIOSTIM model with laboratory tests involving independent flow fields that are characterized using CFD models, so that model predictions of bioluminescence intensity can be compared to experimental results; and (5) couple the BIOSTIM and CFD models to provide a unique flow visualization tool, which can be used to predict bioluminescence signatures for flow fields of naval interest.

APPROACH

The current probabilistic model for bioluminescence stimulation (BIOSTIM) contains three components to allow for: (1) direct stimulation by fluid shear stress, (2) rate-of-change of fluid shear stress, and (3) a memory term to allow for cell desensitization resulting from prolonged exposure to stimulation. The model is based on the fundamental assumption that over any small time interval there is a small but finite chance that a cell will flash, which depends on these three factors. This study considers the case of intense but brief stimulation lasting for no more than a few seconds. In this case we do not have to account for the effects of cell desensitization (von Dassow et al. 2005) and cell memory, greatly simplifying the experiments and analysis required to model the effects of turbulence.

The overall objective of this study is to obtain bioluminescence stimulation data under conditions of high shear stress to feed into the BIOSTIM model, which then is incorporated into CFD models to predict bioluminescence signatures created by bodies traveling in or on the ocean. The most generally applicable simulation techniques are algorithms that solve the Reynolds-averaged Navier-Stokes (RaNS) equations and compute the ensemble-averaged velocities, as well as turbulent energy and energy dissipation fields throughout a given flow, allowing an estimation of local (averaged) turbulent shear stress. The RaNS algorithm to be used in the proposed task is CFDSHIP-IOWA, a well-documented algorithm (Carrica et al. 2006) previously used by PI Hyman and verified with full-scale tests with many types of naval ships. However, such algorithms cannot resolve the very small scales that are responsible for bioluminescent stimulation. The action of such small scale turbulence is approximately characterized by the averaged energy dissipation rate – a modeled quantity. In contrast, the BIOSTIM model, as currently written, is most appropriate for use in a Direct Numerical Simulation (DNS) solver. DNS solutions capture all relevant length and temporal scales in the flow including bioluminescence stimulatory scales (these are in the Kolmogorov or inertial range, depending on Reynolds number). To accomplish this, however, the solvers require extremely fine grids – grids that become too large when flow simulation of model-scale vehicles is attempted and far too large to be considered for full-scale naval vehicles. Therefore the new bioluminescence stimulation model developed in Task 2 will accept the ensemble-averaged flow data produced during a practical flow simulation as a means of determining stimulation probability.

The final task is to validate the updated BIOSTIM model with laboratory tests involving independent flow fields that are modeled using computational fluid dynamics (CFD), so that model predictions of bioluminescence intensity can be compared to experimental results. It is critical to validate the updated BIOSTIM model to determine how predicted results compare to experimental measurements with independent flow fields. The BIOSTIM model is coupled to the CFD model of a body mounted in a flow field to predict levels of stimulated bioluminescence. A new test flume will be designed and fabricated for the validation tests. Bioluminescence will be measured with a low-light digital camera

system to quantify stimulation in the boundary layer and wake regions. The experimental results will then be compared to the coupled BIOSTIM-CFD model predictions.

WORK COMPLETED

The first goal for integrating the computational and experimental activities is to perform direct numerical simulations (DNS) of the flow field associated with a sphere for velocities of 0.5 and 1 m/s, to obtain 2D maps of local fluid shear stress. The current BIOSTIM model has been incorporated into the DNS results to predict levels of stimulated bioluminescence; these predictions are being compared to existing bioluminescence images of a sting-mounted sphere moving at the same speeds in a flume and imaged with a digital low-light camera.

During the present year, considerable effort has been devoted to applying a high accuracy, immersed boundary Cartesian flow solver to compute the flow (and related estimate of bioluminescent stimulation) around a sphere in a channel. The goal is to reproduce images such as that seen in Figure 1, which shows in false color the net light produced from stimulation of dinoflagellates passing by a sphere moving at a speed of 1 m/s.

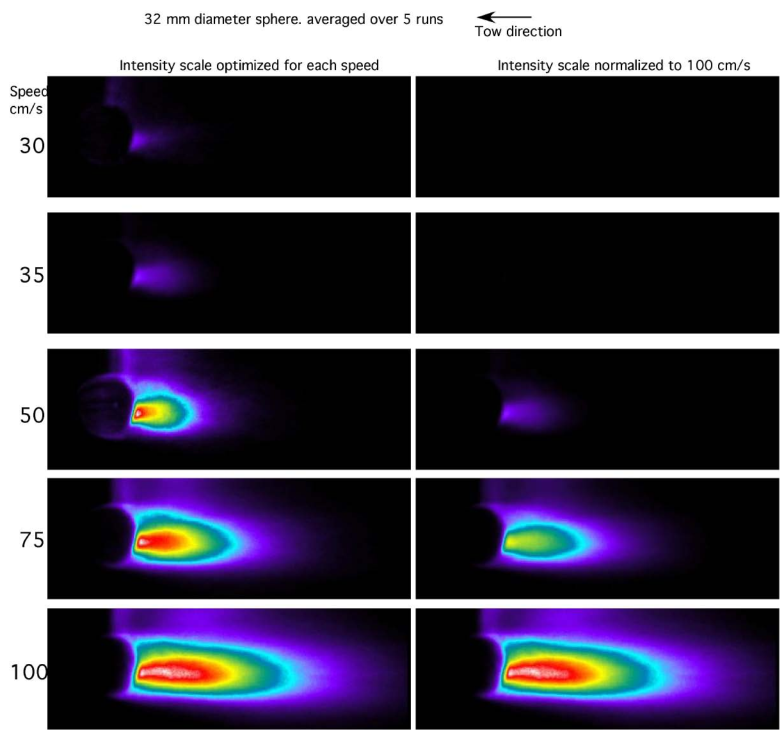

Figure 1. False-color image of bioluminescence of the dinoflagellate Lingulodinium polyedrum stimulated by motion of a 32 mm diameter sphere moving to the left at speeds of 30 to 100 cm/s. The intensity scale goes from low (violet) to high (white). The images show that the luminescent wake of the sphere increases in intensity and length with increasing speed.

The code selected (Yang and Stern 2009) is a scalable, Cartesian solver with discretization stencils up to order 5 in space and order 2 in time. There is a trade-off between resolution of the body geometry and related near-wall region where the boundary layer forms and numerical errors associated with the curvilinear grid used to obtain that resolution. The immersed boundary method does not perfectly

resolve the surface geometry, particularly in high Reynolds number flows. However, it does – by way of the fully staggered Cartesian grid solver – minimize numerical error. The present choice has been to maximize numerical accuracy and give up some geometric accuracy. This choice made in light of the low Reynolds numbers expected in most of the anticipated experimental work.

Initial attempts at using the code indicated a large degree of grid dissipation that should not be seen in higher order numerical methods. The source of the problem was identified and removed and the flow around the sphere at conditions corresponding to 1 m/s was computed with successively finer grids (0.7 million, 5 million and 45 million points, respectively). The grids were built to provide resolution of both the region near the sphere's equator where flow separation was observed to occur in the low resolution grids and in the near-wake where high turbulence (and shear) is likely to be found. The grid used to obtain the results below has a spatial resolution of approximately 250 µm. This is roughly the size of larger bioluminescent organisms. Using this grid size, it can be expected that flow scales on the order of several mm can be resolved reasonably well. Clearly though, it would be desirable to resolve scales that are on the order of an organism. This would allow direct computation of the shear field sensed by the organism and a more direct mechanism of calibrating or modifying the BIOSTIM model.

RESULTS

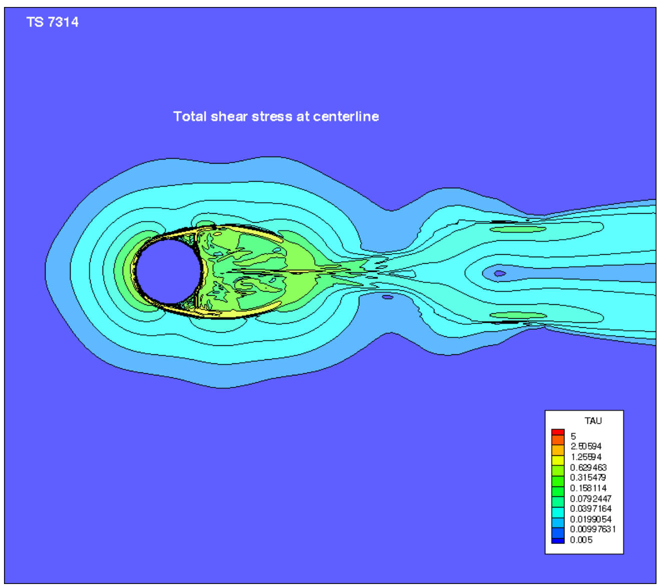

Figure 1. Contour plot of computed shear stress (units of N/m^2) around a sphere. Maximum shear stress occurs just when the flow separates downstream of the sphere equator.

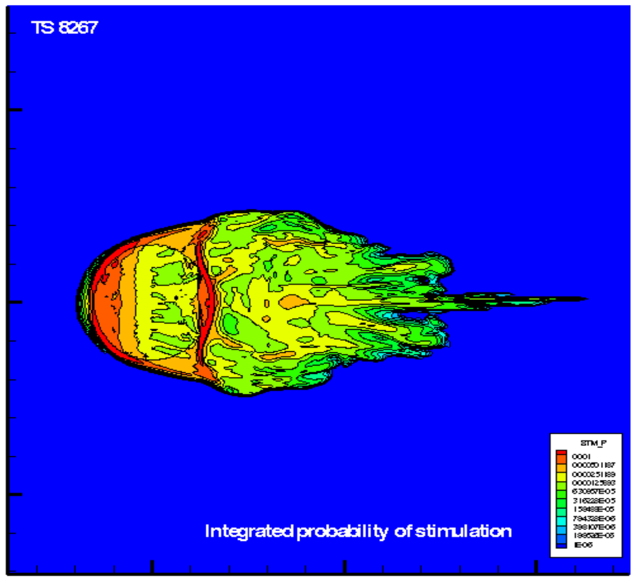

Figure 2. Contour plot of computed bioluminescent stimulation probability around a sphere, based on integrating the computational flow dynamics model with the bioluminescence stimulation model. The highest probability of stimulation occurs on the sphere boundary layer and in the downstream region of recirculating flow.

Flow computations around a 32 mm diameter sphere moving at a speed of 1 m/s were completed during the current year and the results post-processed to give both local shear and bioluminescent potential using the current BIOSTIM model. Figure 2 shows a contour plot of total shear in the center-plane, and Figure 3 shows the integrated stimulation potential estimated by the BIOSTIM model. The flow is fundamentally unsteady so instantaneous results such as those shown are a little misleading. Light used to generate the photographic image in Figure 1 is gathered over a longer period of time than the $3x10^{-6}$ time-step used in the computation. Flow unsteadiness is hinted at by the general structure of results (axial flow, shear and stimulation probability) each computed at a different time step. An animation of any of these phenomena shows unsteadiness more clearly. The results suggest that progress is being made but raises several issues – whether the high values of stimulation probability computed on the sphere upstream face is real and why there is a similar but weaker downstream high stimulation probability that does not appear in the photographic image. The appearance of high stimulation probabilities on the upstream face is reasonable given the high shear and thin boundary layer but its thickness suggests that the geometric inaccuracy related to the immersed boundary method may play a role. This phenomenon is less likely to be a factor on the downstream face where recirculating flow is likely to produce high values of shear. In viewing Figure 3, it is necessary that the three-dimensionality of the plot be considered – the contour plot is an integration in the in-page direction and the high values of stimulation probability are the result of viewing an axisymmetric field in 2-D; i.e., the large shear just downstream of the sphere equator can be misconstrued as shear on the downstream face.

These initial comparisons must be revisited as the calculation matures. Once results are obtained at a grid resolution that is closer to that needed to compute shear across an organism, then it will be appropriate to average the a number of computational “frames” and compare to photographic data.

IMPACT/APPLICATIONS

Project results will enhance DoD capability for predicting levels of bioluminescence associated with surface and underwater vehicles of naval interest. The BIOSTIM model can be used in applications involving swimmer delivery vehicles and other submersible platforms, as well as torpedoes and other high-speed objects. The breakthrough in providing this capability is the development and application of the BIOSTIM model, developed by Deane and Stokes, that forms a theoretical basis for studying the relationship between flow stimulation and the bioluminescence response. The BIOSTIM model, when coupled to computational hydrodynamics models that provides values of shear stress for a given flow field, allows for predictions bioluminescence intensity for a given level of bioluminescence potential, either measured directly or obtained from the NAVOCEANO METOC database once a transfer function between the flow agitator and flow field is known.

A coupled BIOSTIM-CFD model introduces a new predictive capability for estimated bioluminescence signatures. A validated model can then be verified with full-scale experiments with surface ships and underwater vehicles of naval interest. In situations where field tests are not possible, once a transfer function between the flow agitator and flow field is known, it can be used with the NAVOCEANO METOC database of bioluminescence potential measurements to predict bioluminescence signatures in essentially any oceanic region. The Non-acoustical Optical Vulnerability Assessment Software (NOVAS) being developed by NRL (Matulewski and McBride 2005) has a placeholder in which the coupled BIOSTIM-CFD model can be incorporated into the nighttime visibility assessment component.

RELATED PROJECTS

The objectives of this project are complimentary and related to the objectives of an NSF funded project to better understand energy dissipation within breaking wave crests using the bioluminescent flash response of dinoflagellates as a flow visualization tool.

REFERENCES

Carrica, P. M., W. R. V., and S. F. 2006. Unsteady rans simulation of the ship forward speed diffraction problem. Computers & Fluids 35: 545-570.

Deane, G. B., and M. D. Stokes. 2005. A quantitative model for flow-induced bioluminescence in dinoflagellates. Journal of Theoretical Biology 237: 147-169.

Latz, M. I., J. F. Case, and R. L. Gran. 1994. Excitation of bioluminescence by laminar fluid shear associated with simple Couette flow. Limnol. Oceanogr. 39: 1424-1439.

Latz, M. I., A. R. Juhl, A. M. Ahmed, S. E. Elghobashi, and J. Rohr. 2004. Hydrodynamic stimulation of dinoflagellate bioluminescence: a computational and experimental study. J. Exp. Biol. 207: 1941-1951.

Latz, M. I., and J. Rohr. 1999. Luminescent response of the red tide dinoflagellate *Lingulodinium polyedrum* to laminar and turbulent flow. Limnol. Oceanogr. 44: 1423-1435.

Maldonado, E. M., and M. I. Latz. 2007. Shear-stress dependence of dinoflagellate bioluminescence. Biol. Bull. 212: 242-249.

Matulewski, K. V., and W. McBride. 2005. Day/night underwater object detection from an airborne sensor using NOVAS (Non-acoustical Optical Vulnerability Assessment Software), p. 2274. OCEANS, 2005. Proceedings of MTS/IEEE.

von Dassow, P., R. N. Bearon, and M. I. Latz. 2005. Bioluminescent response of the dinoflagellate *Lingulodinium polyedrum* to developing flow: Tuning of sensitivity and the role of desensitization in controlling a defensive behavior of a planktonic cell. Limnol. Oceanogr. 50: 607-619.

Yang, J., and F. Stern. 2009. Sharp interface immersed-boundary/level-set method for wave-body interactions. J. Computational Physics 228: 6590-6616.